Probing Technivector Scenarios at the LHC

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+ work in progress

Fermilab, 2008

Motivation:

Strong EW-scale interactions are a possibility at the LHC; to be as prepared as possible we could:

- Hope there are no new strong interactions
- Solve strong interactions completely
- Use the lattice
- Develop generic, flexible scenarios useful for detailed phenomenology

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Outline:

- Strong interactions at the LHC:
  what's been done
- Parameterizing Technivector scenarios:
  - Higgsless basics
  - Extending higgsless techniques
  - Parameter constraints
- Phenomenology examples;
  low + high luminosity signals

What we know:

- Strong interactions are difficult!
- Rescaled QCD models are ruled out:

$$f_\pi \to v$$
$$\pi_a \to W_L, Z_L$$
$$\rho, a_1 \to \rho_T, a_T$$

S parameter:

$$S > 0, \mathcal{O}(1)$$

but, not generic:

Meson spectrum sensitive to $m_q,\ \Lambda_{UV},\ \beta(\alpha_s)$

- EW scale strong interactions must be very different from QCD -- But then how do we calculate?
- Many attempts have been made...

What's been done:

Very few collider studies!

- 4D:

  Walking Technicolor (Lane)
  Topcolor (Hill)
  Low-Scale TC (LSTC) (Lane)
  (D)BESS (Casalbuoni et al)
  Low-N TC (Sannino)
  Deconstructed Higgsless (Chivukula)
  ...

Full Collider Study

Parton Level

- 5D:

  Higgsless (Csaki et al)
  Composite Higgs (Pomarol et al)
  ...

Common feature: TeV scale spin-1 resonances (ρ_T, W_{KK})

Moving beyond Models: Proposal

- Most general $\mathcal{L}(\mathrm{SM} + \mathrm{spin}-1)$ has $\mathcal{O}(100)$ parameters
  → way too many for practical pheno!

  Need an organizing principle

- Start by extending Higgsless techniques; Can we expose new + distinct features?

- NOT a new model, RATHER an organizing scheme

- Implement this scheme into matrix-element generator

  No models currently implemented!

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a DEWSB equivalent of what mSUGRA is for MSSM

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Short answer: Yes

- NOT a new model, RATHER an organizing scheme
- Implement this scheme into matrix-element generator

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Higgsless Basics:

- AdS/CFT inspired 5D version of strong DEWSB

- 5D interval $z \in (\ell_0, \ell_1)$; containing
  $SU(2)_L \otimes SU(2)_R$ gauge fields.

- Bulk geometry usually: $\frac{\ell_0^2}{z^2}(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$

- BC break EWS $\longrightarrow$ KK tower of states;
  zero modes are $\gamma, W^\pm, Z^0$
  +Vector, Axial resonances (not quite!): $W_n^\pm, Z_n$

- Resonancs couplings: $g_{ABC} \propto \int_{\ell_0}^{\ell_1} dz \frac{\ell_0}{z} \phi_A(z) \phi_B(z) \phi_C(z)$

Higgsless cont.

- small $g_5 \longleftrightarrow$ large N_{TC}
- Spectrum: tower of narrow, weakly interacting resonances (large N_{TC})

  → large coupling to W_L, Z_L comes from plugging in polarizations

  → exchange of many resonances delays unitarity violation
- BUT, pure AdS leads to QCD-like spectrum (Agashe et al '07)

  $S > 0, \ \mathcal{O}(1)$; Small perturbations don't help

Models can be made viable at the expense of $g_{ffV} \cong 0$ ⇒ Limited Phenomenology

Our scheme: Modifying Higgsless

- How can we extend the Higgsless framework to incorporate new features?

- Effective warp factors:

$$\mathcal{L} = -\frac{1}{2g_5^2}\int dx\, \omega_V(z) F_{V,NM} F_V^{NM} + \omega_A(z) F_{A,MN} F_A^{MN}$$

$$\omega_{V,A}(z) = \frac{\ell_0}{z}\exp\left(o_4^{V,A}\left(\frac{z}{\ell_1}\right)^4\right) \qquad o_V, o_A < 0$$

(Hirn, Sanz '06,'07)

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(Hirn, Sanz '06,'07)

Positive definite

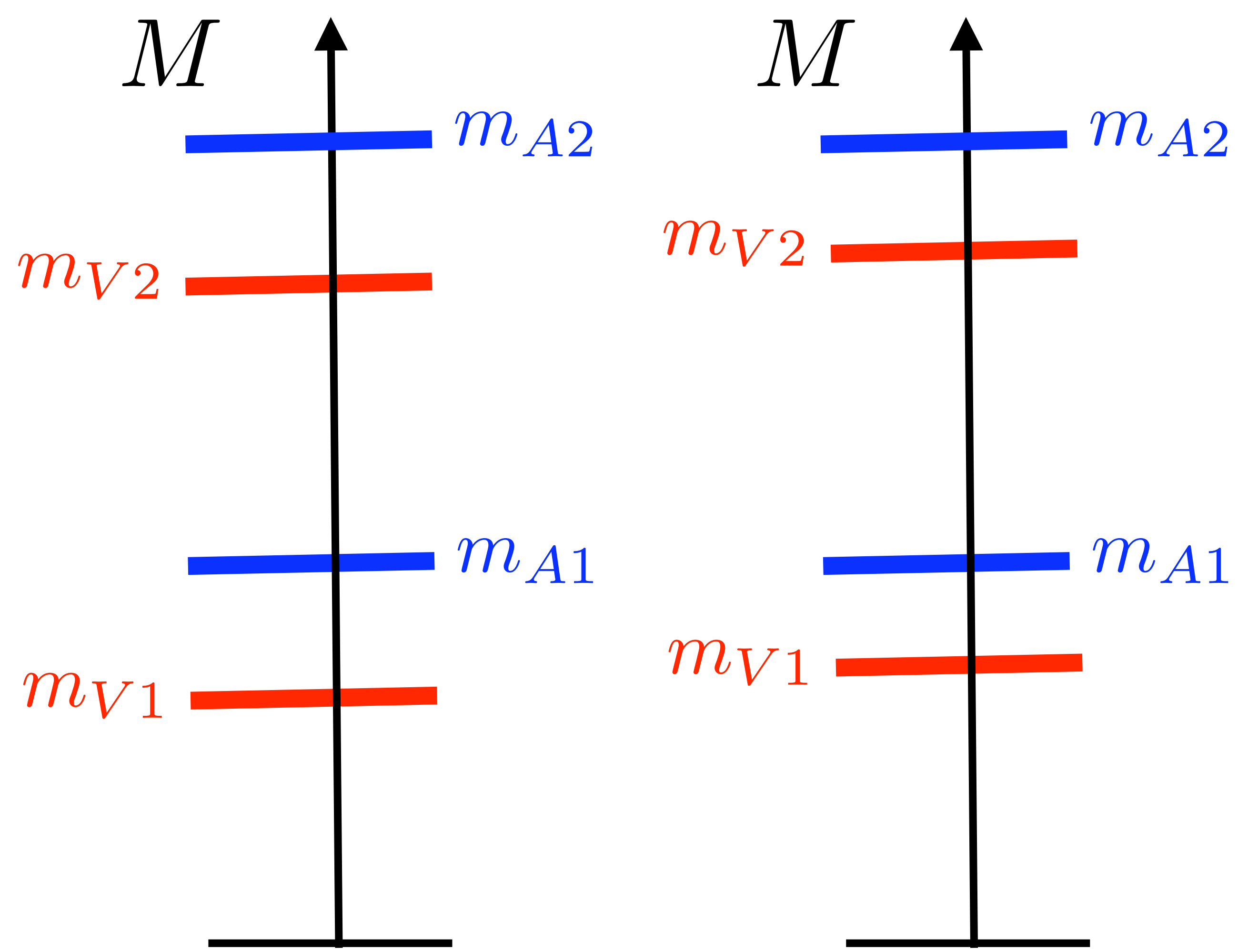
Deformed in IR - power of z unimportant

Acts like condensate

$$\Pi_{V,A} \sim \frac{o_{V,A}}{(Q\ell_1)^4}$$

Why this deformation? $\omega_{V,A} = \frac{\ell_0}{z} e^{o_{V,A} z^4/\ell_1^4}$

- Allows us to vary the length of the dimension the vector feels relative to the axial



$o_V = 0, o_A = 0$

Dialing o_V for fixed o_A :

Remember:

Eigenstates $W^{\pm}_{1,2}, Z^0_{1,2}$ are a mixture of V, A

$$|\psi_X(z)\rangle = |V_X(z), A_X(z)\rangle$$

- Added only 2 new parameters, no new fields
- Couplings $g_{W_1 W Z}$, etc. will also vary with ℓ_1, o_V, o_A

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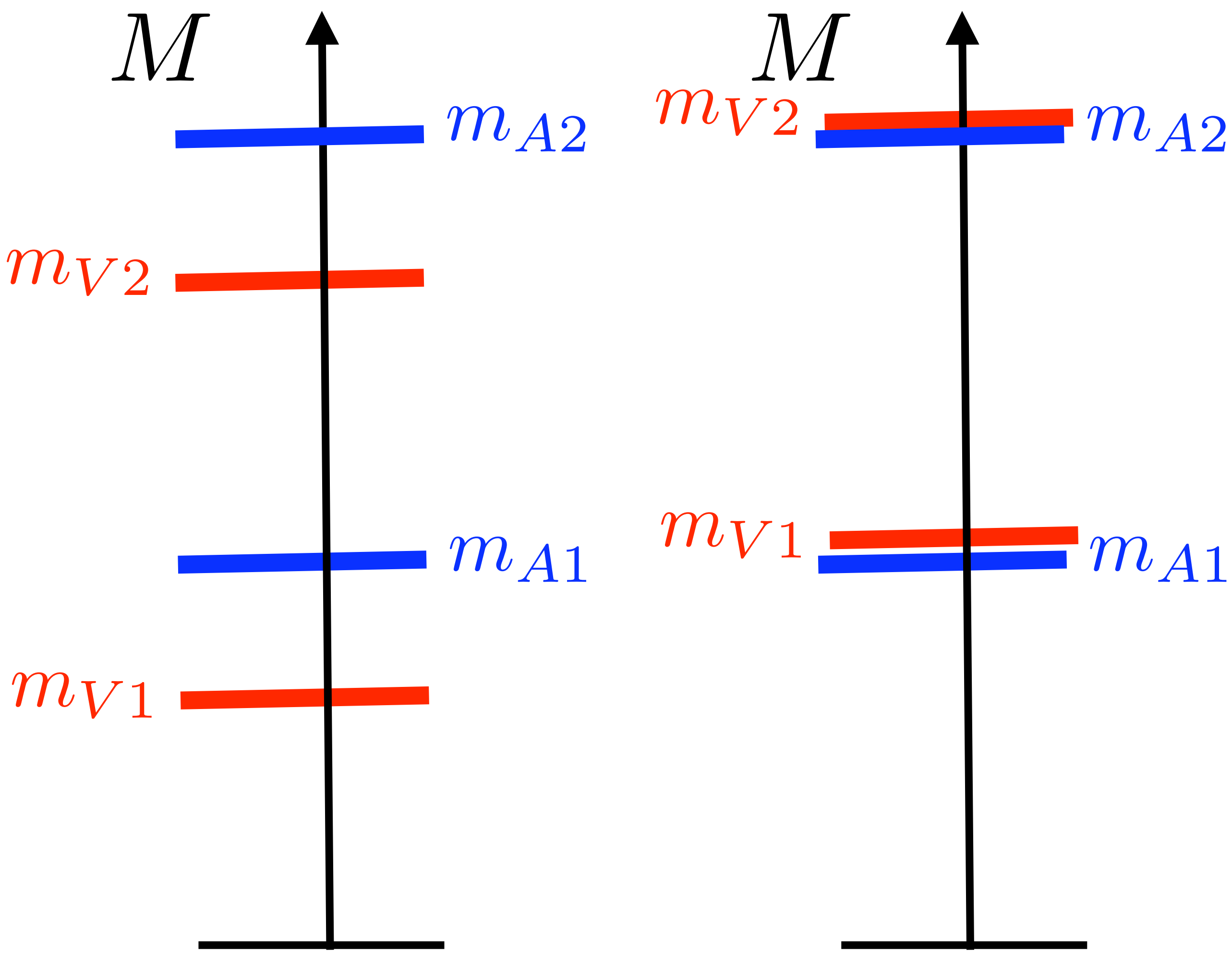

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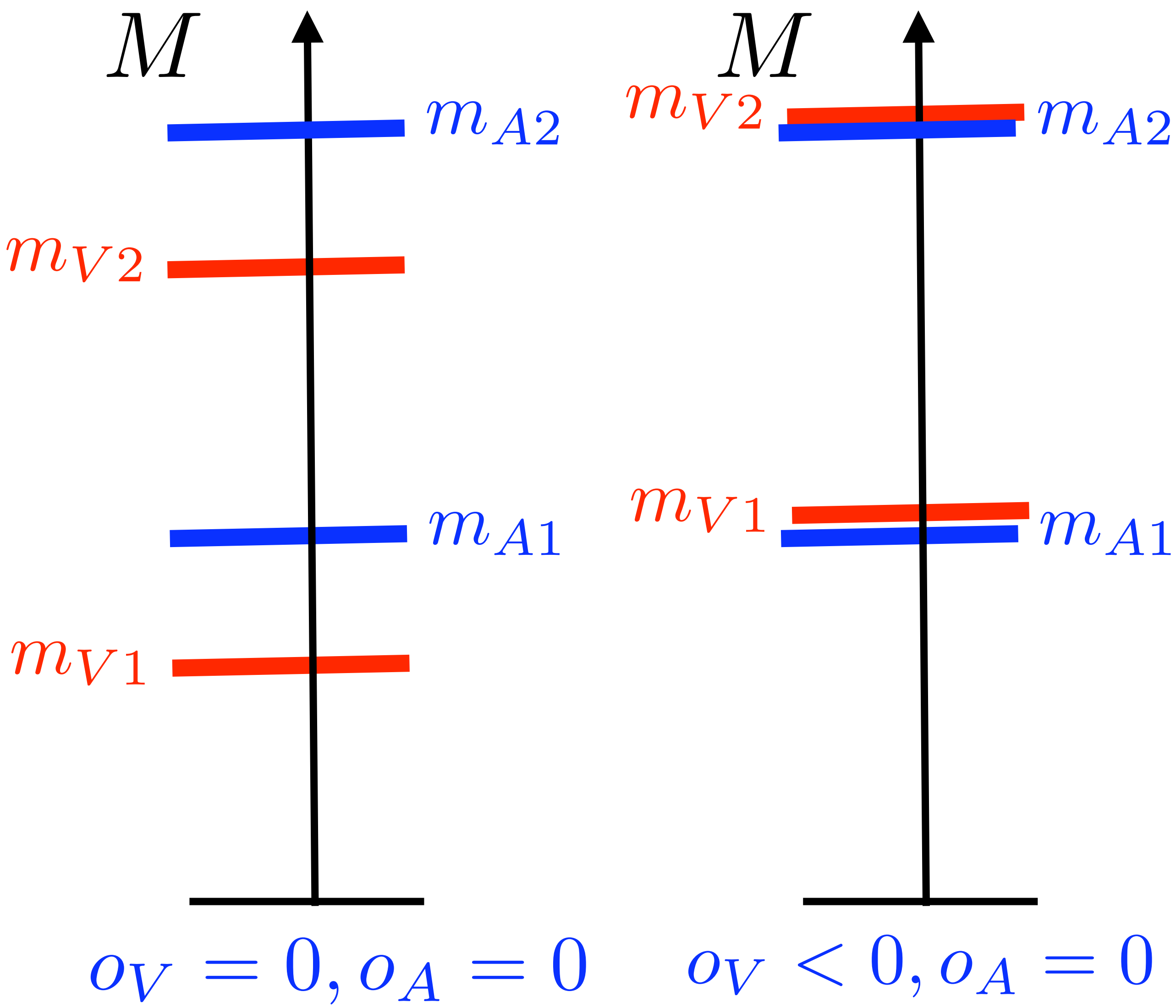

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Degenerate spectrum

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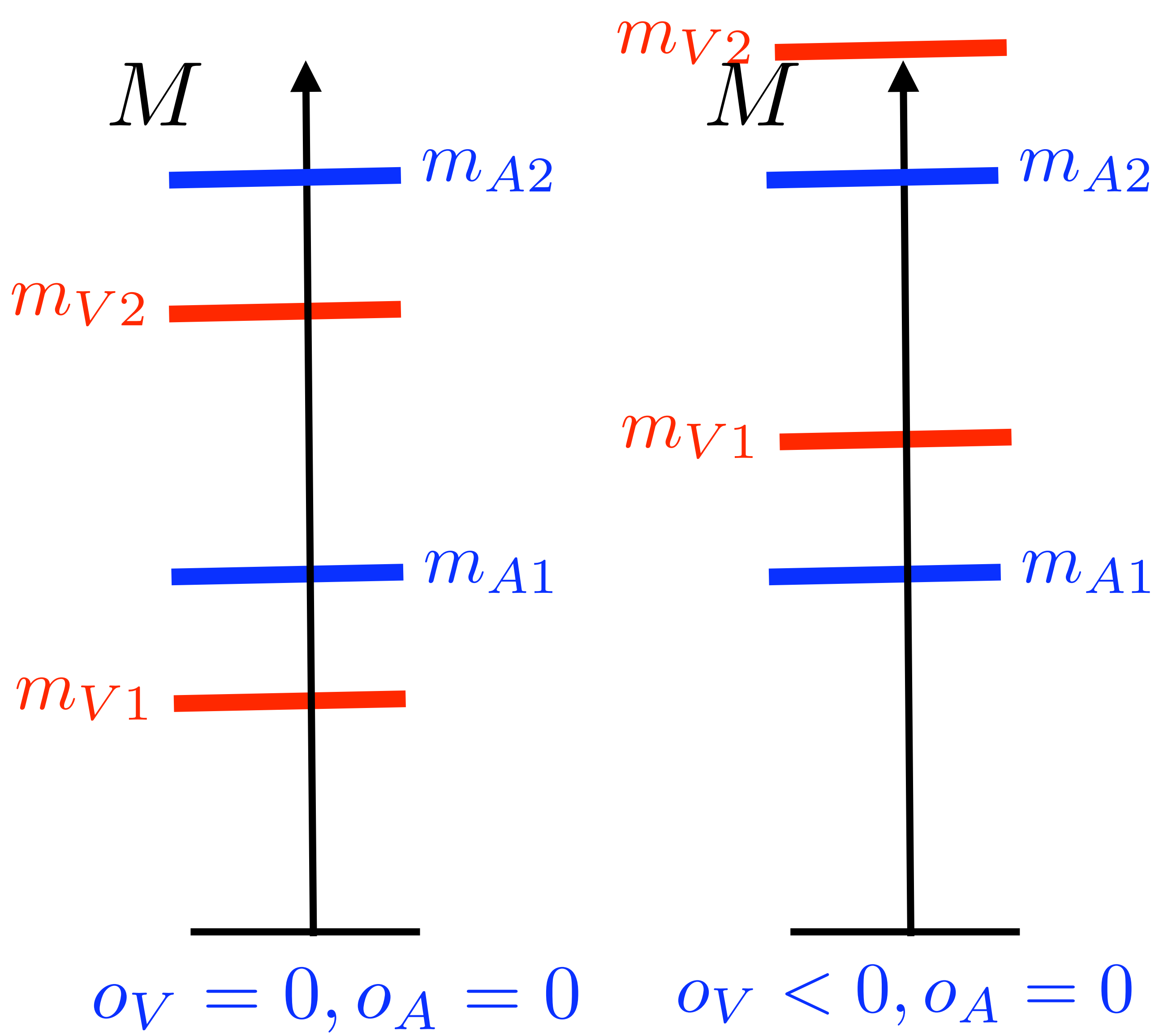

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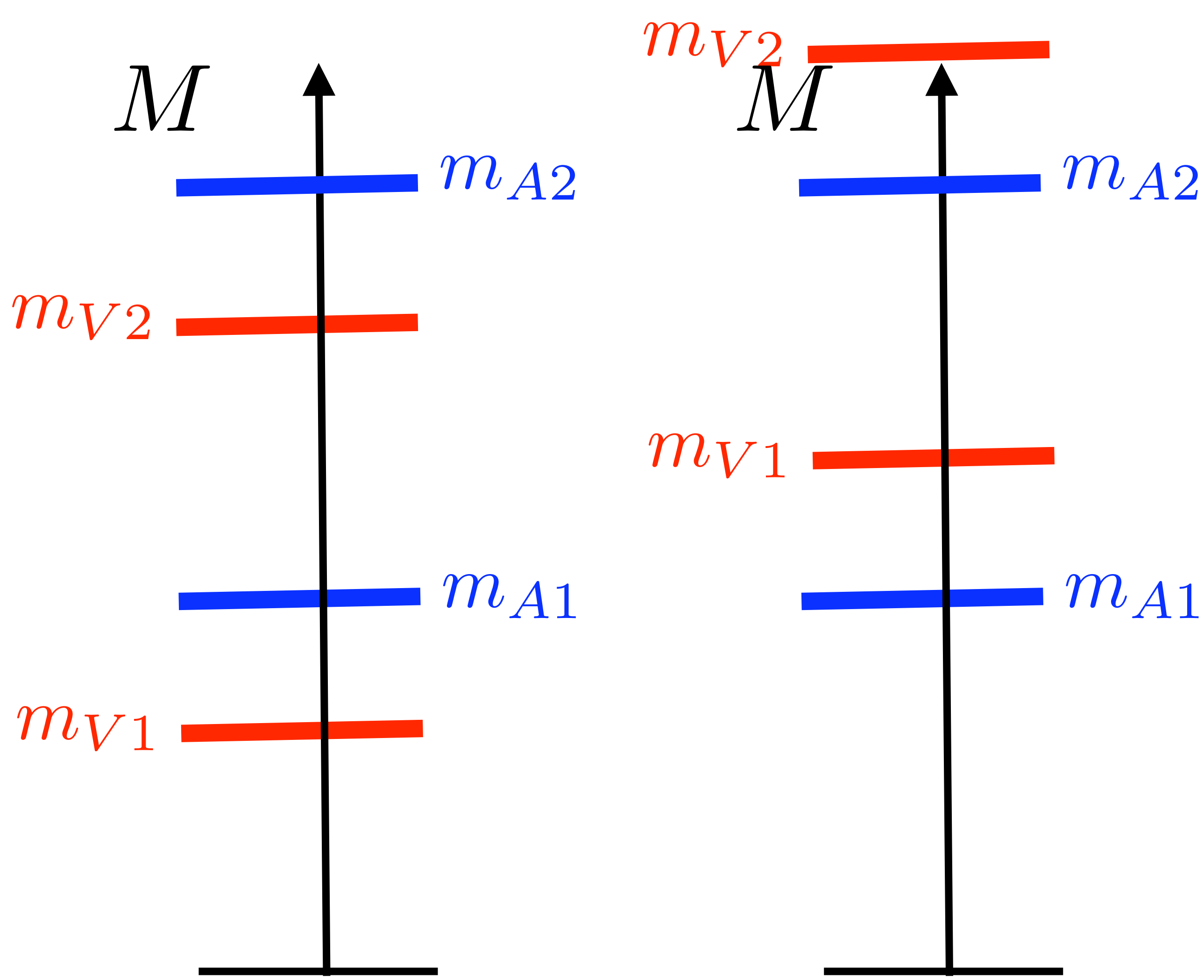

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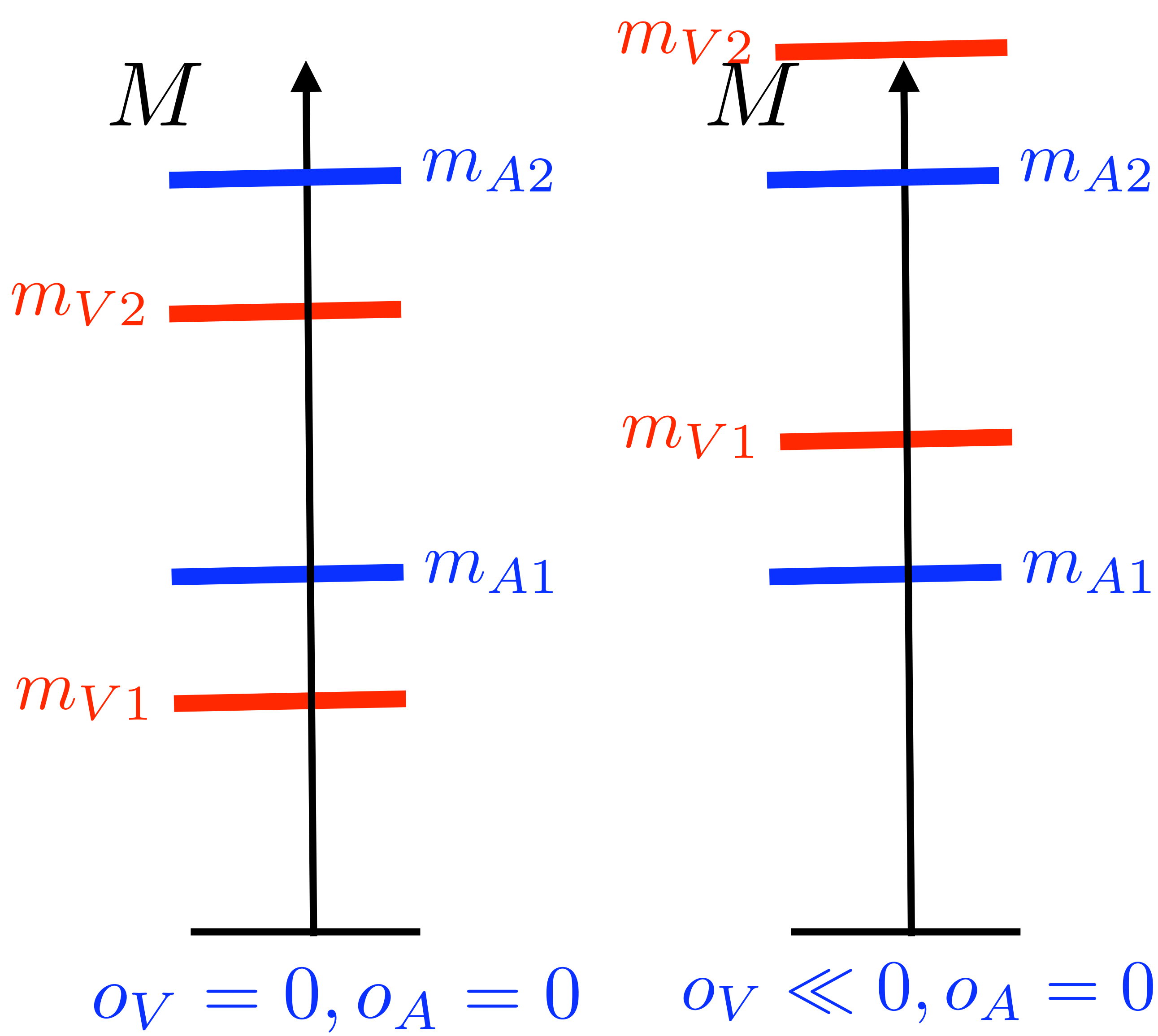

Dialing o_V for fixed o_A :

or Inverted spectrum

Remember:

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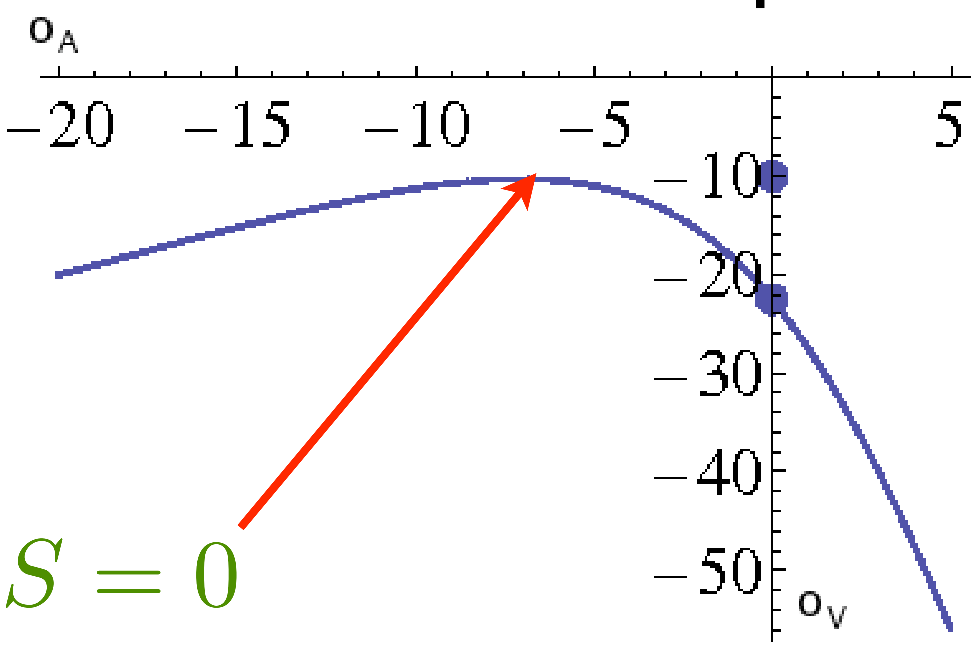
What do we gain?

- Cancellation in S possible!



When $S \sim 0$; nearly degenerate resonances

$$M_{W_1} \cong M_{W_2}$$

Expected! (Appelquist `99)

- Whenever $\omega_V \neq \omega_A$; unconventional triboson, 4-boson couplings

$$g_{W_1^- WZ} = g_1 \partial_{[\mu} W_{1\nu]}^- (W_{[\mu}^+ Z_{\nu]}^0) + g_2 \partial_{[\mu} W_{\nu]}^- (Z_{[\mu}^0 W_{1\nu]}^-) + g_3 \partial_{[\nu} Z_{\nu]}^0 (W_{[1\nu}^- W_{\nu]}^+)$$

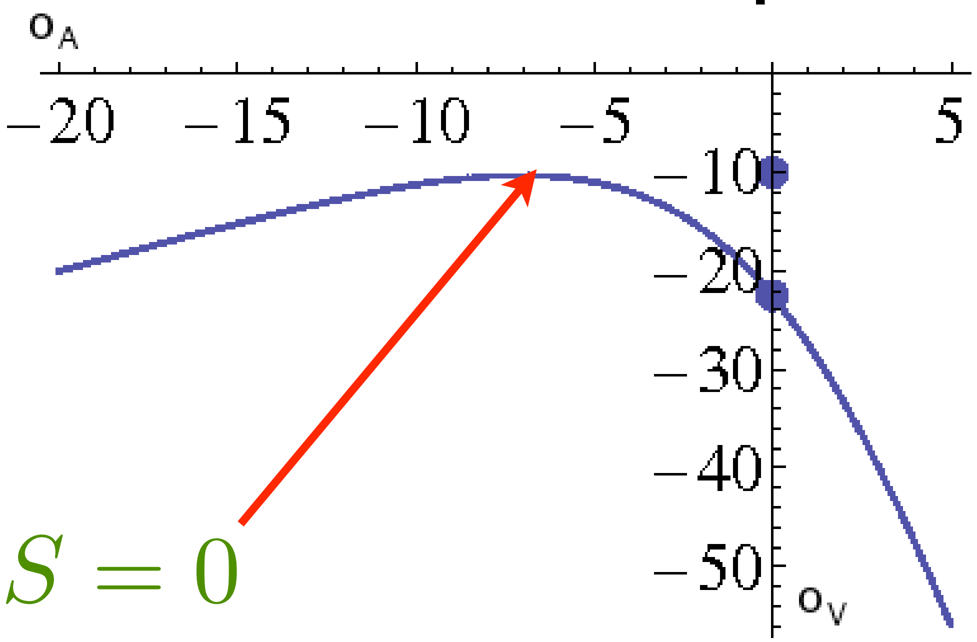
$$g_1 \supset \int_{\ell_0}^{\ell_1} dz\ \omega_V (V_1 A_{W^+} A_Z) \cdots \neq g_3 \supset \int_{\ell_0}^{\ell_1} dz\ \omega_A (V_1 A_{W^+} A_Z) \cdots \neq g_2$$

Mixed photon coupling $g_{W_1^- W^+ \gamma}$ can be nonzero!

What do we gain?

New pheno. and a new twist on old pheno.

- Cancellation in S possible!



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What about SM fermions?

- Coupling of fermions to the new resonances will determine the best production methods at the LHC
- Full 5D treatment of fermions would re-introduce many parameters...

For starters: one more parameter g_{ffV}

$$g_{ffW} = g_{SM}$$

- We can study several models of fermion interactions

$$g_{ffV} = \kappa \, g_{ffW}$$

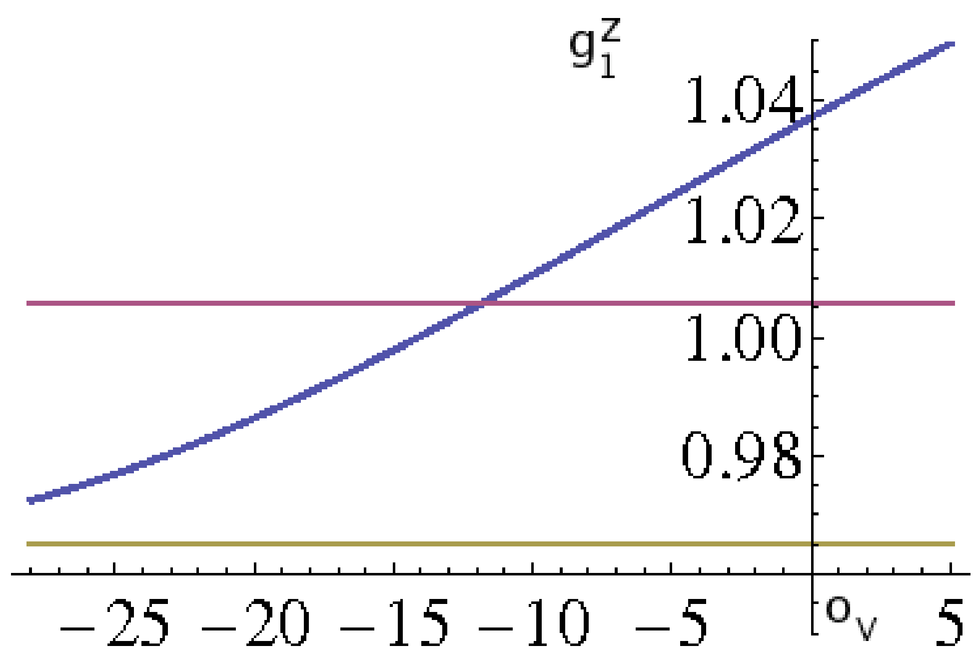
$$g_{ffV} \cong 0 \qquad \text{ideally delocalized}$$

$$g_{t_R t_R V} \gg g_{ffV} \qquad \text{mostly composite } t_R$$

Constraints:

- Parameter count: $\ell_1, \ell_0, g_5, \tilde{g}_5, o_V, o_A, g_{ffV}$

- For a given ℓ_1: o_V, o_A constrained by anomalous $g_{WW\gamma}$, g_{WWZ} couplings (LEP).



- LEP, Tevatron constrain fermion-resonance coupling

  contact interactions: $\frac{(\bar{f}f)(\bar{f}'f')}{\Lambda^2}$

  direct bounds: $\sigma(p\bar{p} \to Z'(W') \to \ell^+\ell^-(\ell\nu))$
  indirect bounds: # high p_T objects (Z^0, γ)

Constraints:

overall scale: $M_{res} \sim \frac{1}{\ell_1}$

- Parameter count: $\ell_1, M_Z, M_W, \alpha_{em}, o_V, o_A, g_{ffV}$

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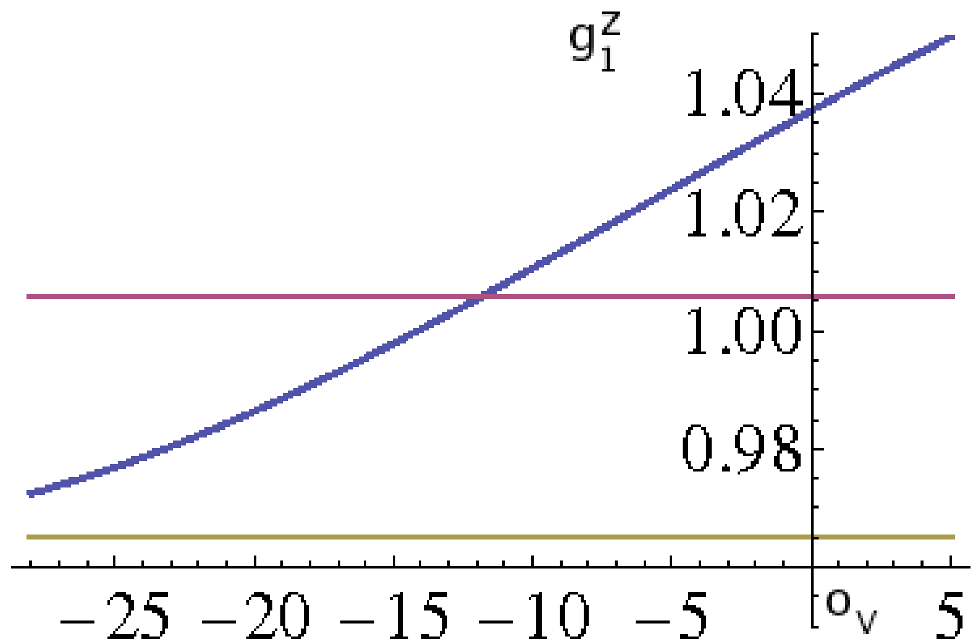

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Our Scheme: Review

$$\mathcal{L} \supset \mathcal{L}_{spin-1} + \mathcal{L}_{res+WZ\gamma} + g_{f_i f_j V}\bar{\psi}_i\gamma_\mu\psi_j V^\mu + g_{f_i f_j W}\bar{\psi}_i\gamma_\mu\psi_j W^\mu$$

5D modeled

$\omega_V \neq \omega_A$

- new spectrum + interactions
- anomalous couplings $g_{WWZ} \neq (g\cos\theta_W)_{SM}$

Pheno. coupling

$g_{ffV} = \kappa\, g_{ffW}$

- LEP , Tev. bounds

SM values:

- We are NOT solving PEW problems here
- We ARE generating viable scenarios with new phenomenological features to be studied

Why 5D?

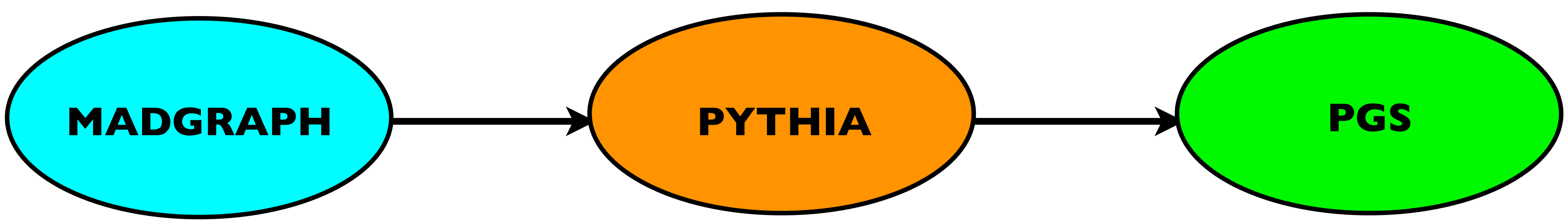
Certainly more ways to get $\mathcal{L}_{spin-1}$:
(mooses, HLS)

5D:

- Flexible spectrum/interactions with only 2 free parameters + no new fields
- Setup easily put into unitary gauge and mass eigenstates → Simplifies implementation into MC programs
- Easy to add more resonances later on;
  (isosinglet resonances ω_T, scalars, fermions)

Next step:

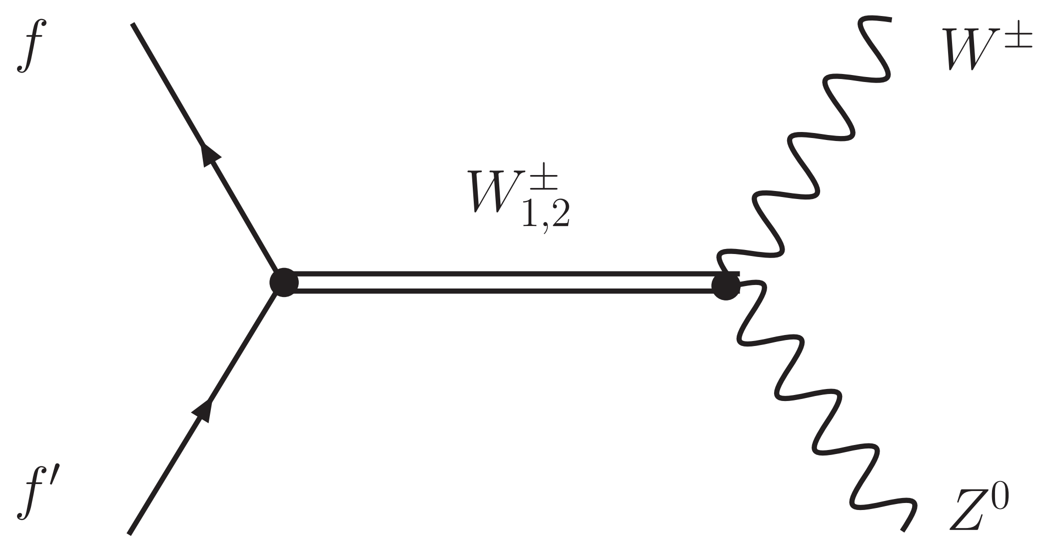
- Put first two resonance multiplets + interactions into matrix element generator MadGraph



Low Luminosity Signals: Drell-Yan

- Nonzero fermion-resonance coupling:

  → Drell-Yan is the dominant production mode



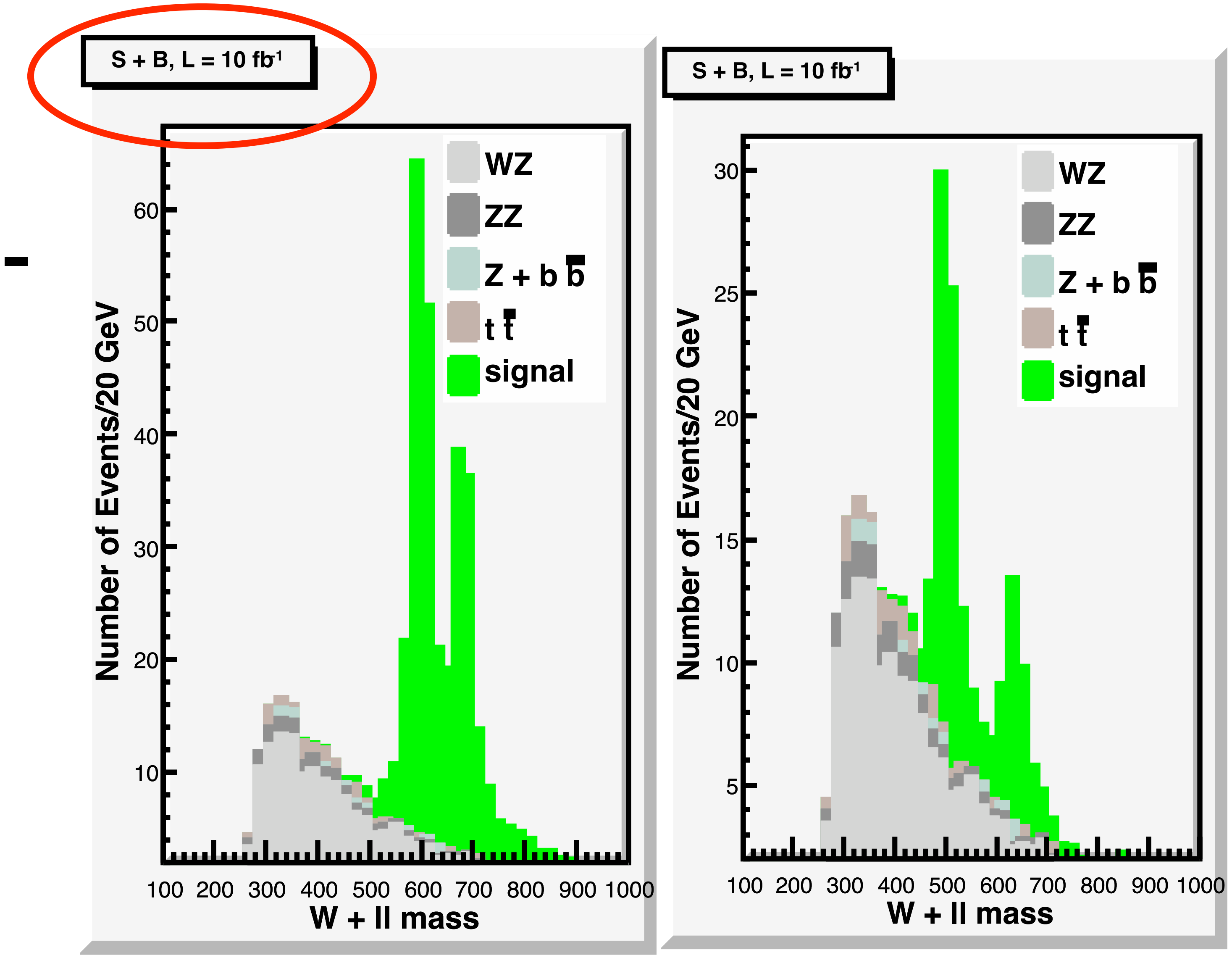
- Choosing couplings to satisfy all LEP + Tevatron constraints, we can still get a spectacular signal.

$$\sigma(pp \to W_{1,2} \to WZ) \propto \frac{M^4_{W_{1,2}}}{M_Z^2 M_W^2}$$

Enhancement from decays to longitudinal polarizations

Example: $pp \to W^{\pm}Z \to 3\ell + \nu$

- Two resonances - both couple to $W^{\pm}, Z^0$
- Seen within the first few fb^{-1} at LHC



1.) $n_{lep} = 3, p_T > 10$ GeV, $|\eta| < 2.5$
$p_T > 30$ GeV for at least one

2.) $|M_{\ell^+\ell^-} - M_Z| < 3.0\Gamma_Z$

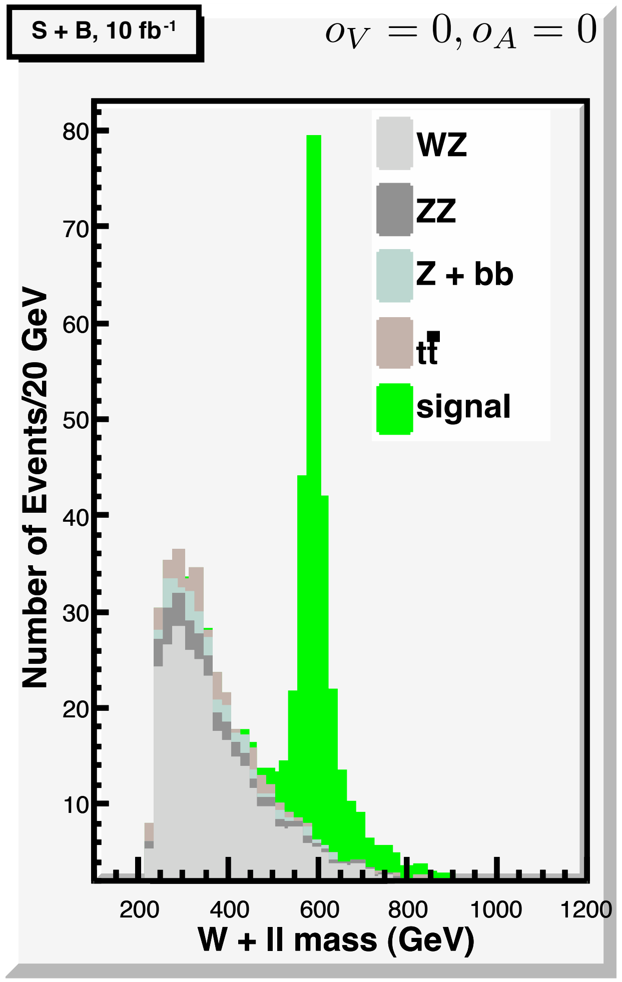
3.) $H_{T,jets} < 125$ GeV

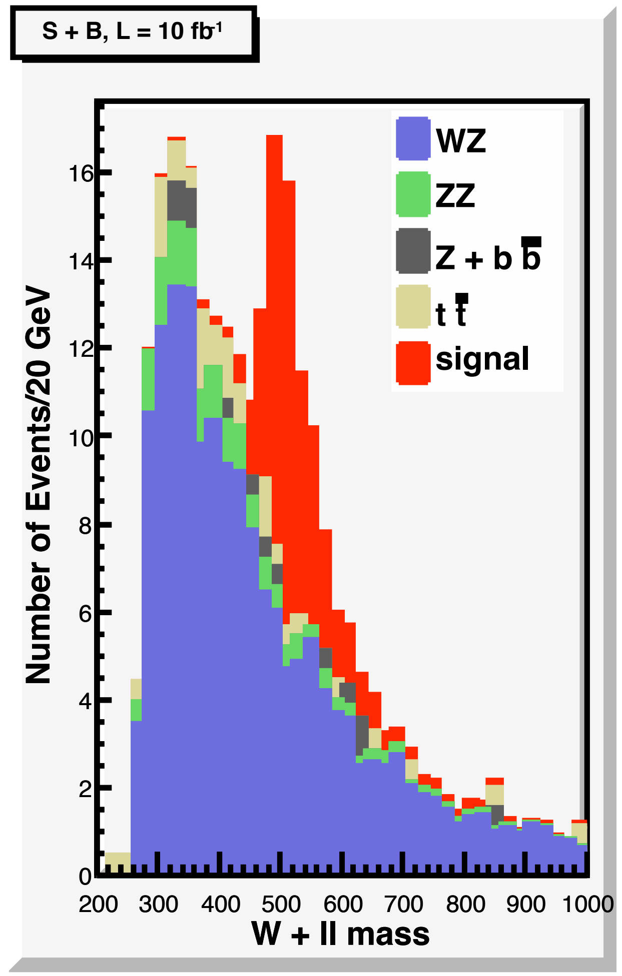
4.) $p_{T,W},\ p_{T,Z} > 100$ GeV

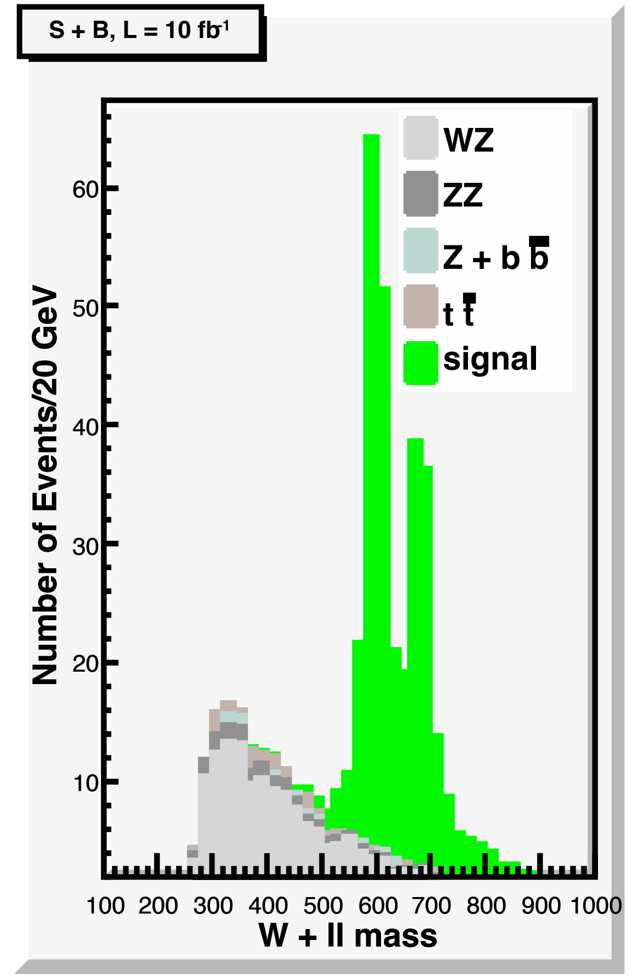
All plots:

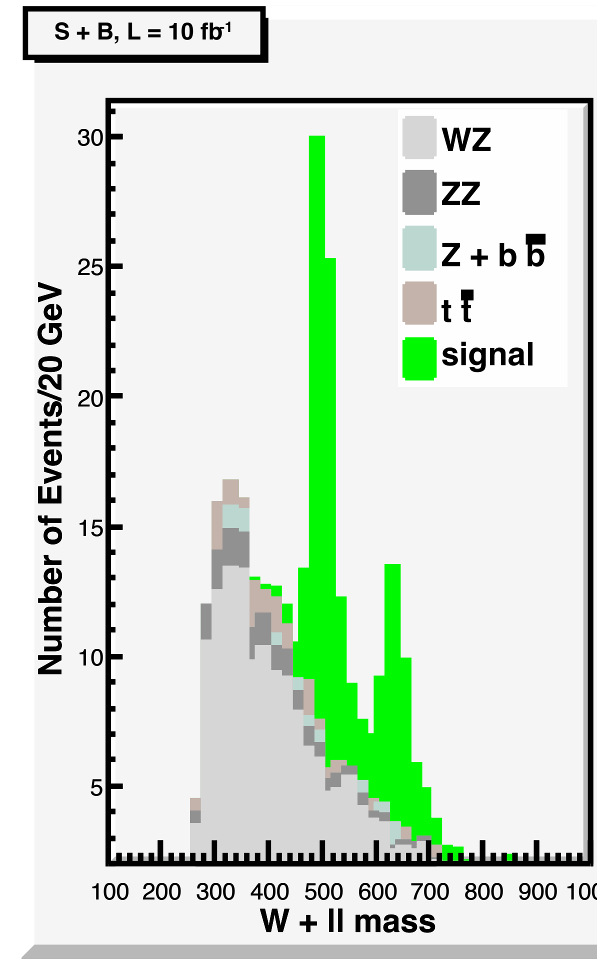
MadGraph ⟶ PYTHIA ⟶ PGS

Comparison: $pp \to W^{\pm}Z \to 3\ell + \nu$









Pure AdS **Low-Scale TC** | **Effective Warp Factors**

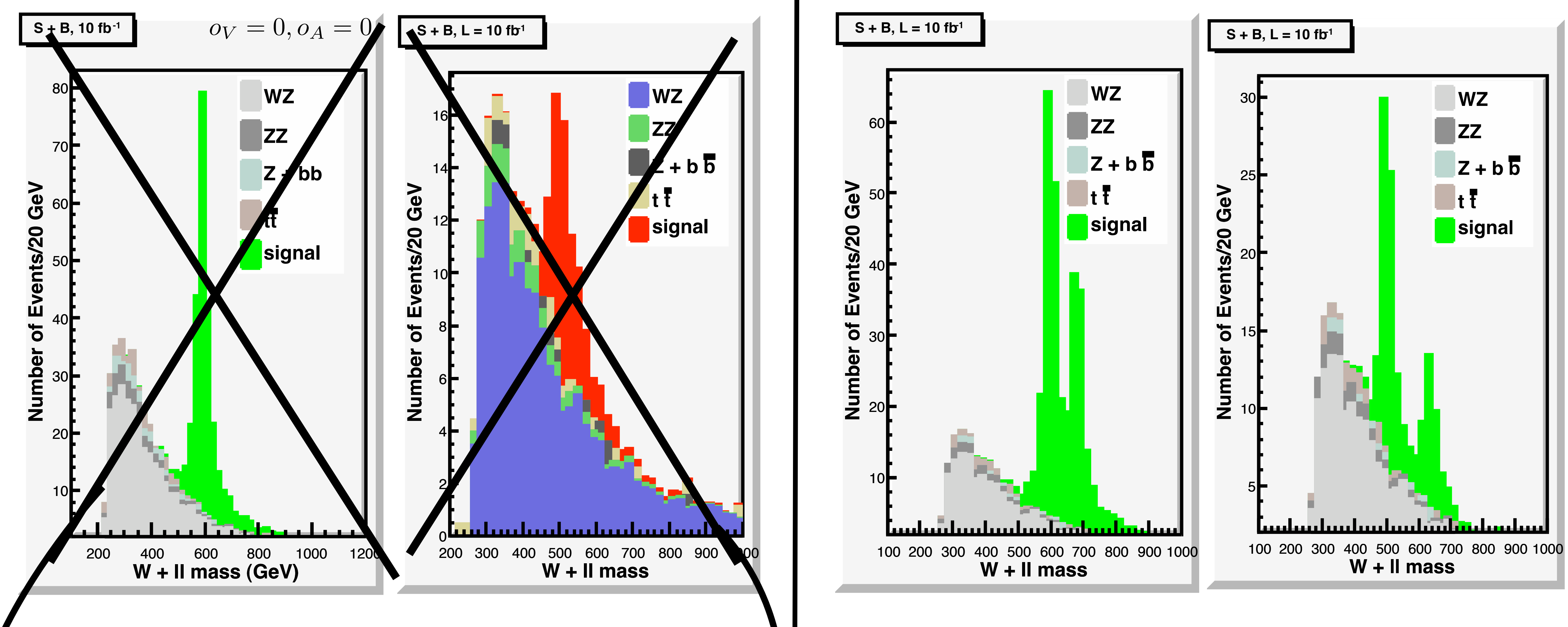
Only one peak

$M_{W_2} \gg M_{W_1}$ or no g_{W_2WZ}

Two peaks

$M_{W_2} \cong M_{W_1}$, $g_{W_2WZ} \neq 0$

Comparison: $pp \rightarrow W^{\pm}Z \rightarrow 3\ell + \nu$



Pure AdS

Not allowed by g_{WWZ}

Low-Scale TC

PEW incalculable

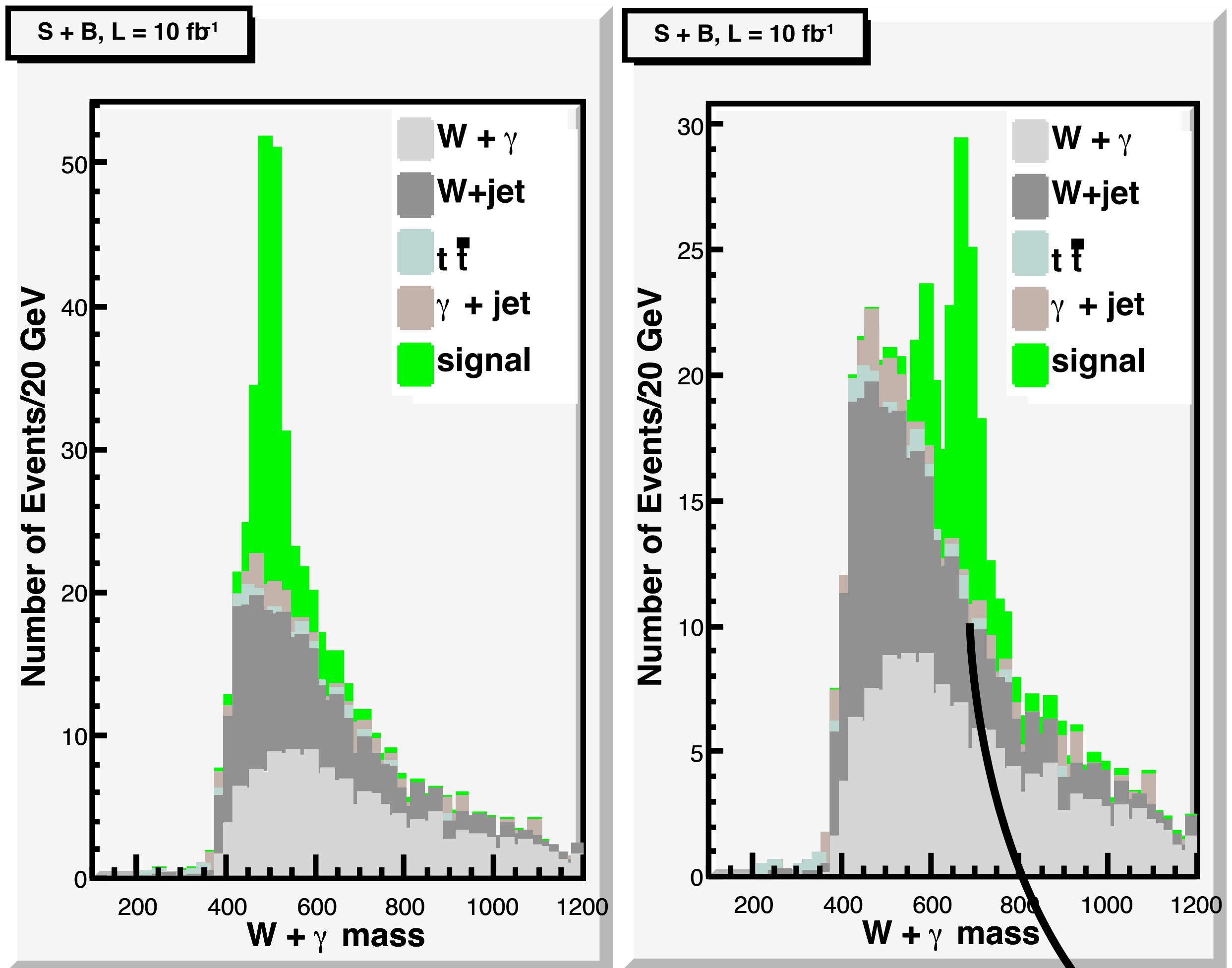
Effective Warp Factors

Satisfies all experimental constraints

Example: $pp \to W^{\pm}\gamma \to \ell + \nu + \gamma$

When $\omega_V \neq \omega_A$: $g_{\gamma W^+ W_1^-} \partial_{[\mu}\gamma_{\nu]}(W^+_{[\mu} W^-_{1\nu]}) \neq 0$

is allowed, NOT permutations



1.) $n_{lep} = 1, p_T > 10$ GeV, $|\eta| < 2.5$

2.) $n_\gamma = 1, p_T > 180$ GeV, $|\eta| < 2.0$

3.) $p_{T,W} > 180$ GeV

4.) $E_{T,miss} > 20.0$ GeV

$g_{W_1 W \gamma}$

- Does not exist in AdS Higgsless

$g_{H^\pm W \gamma}$

- Only at loop level in MSSM/ 2HDM

Two peaks when:

$M_{W_2} - M_{W_1} \lesssim 90$ GeV

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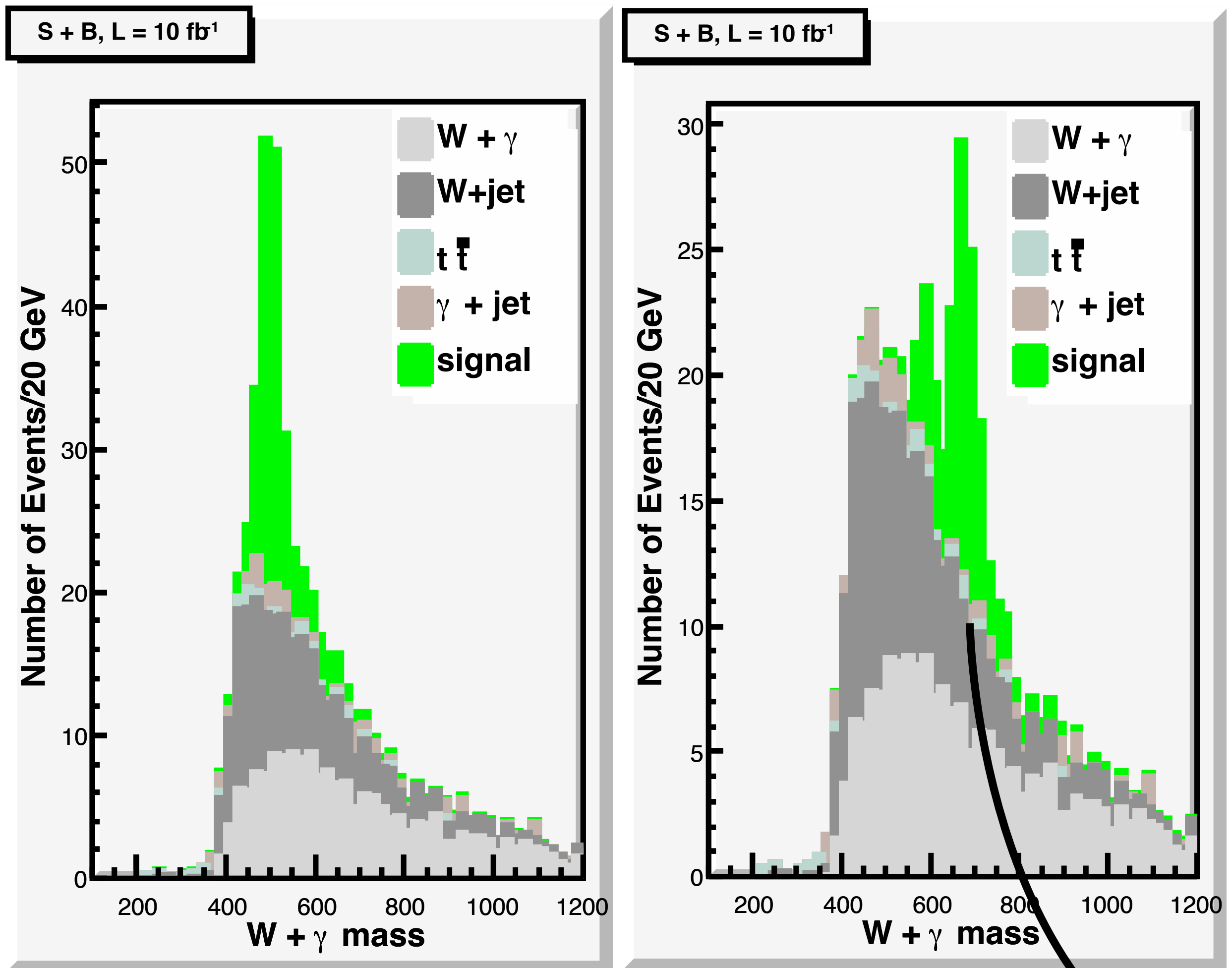

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$g_{H^{\pm} W \gamma}$

- Only at loop level in MSSM/2HDM

New Signal!

Two peaks when:

$M_{W_2} - M_{W_1} \lesssim 90$ GeV

Beyond $M_{W_{1,2}}$:

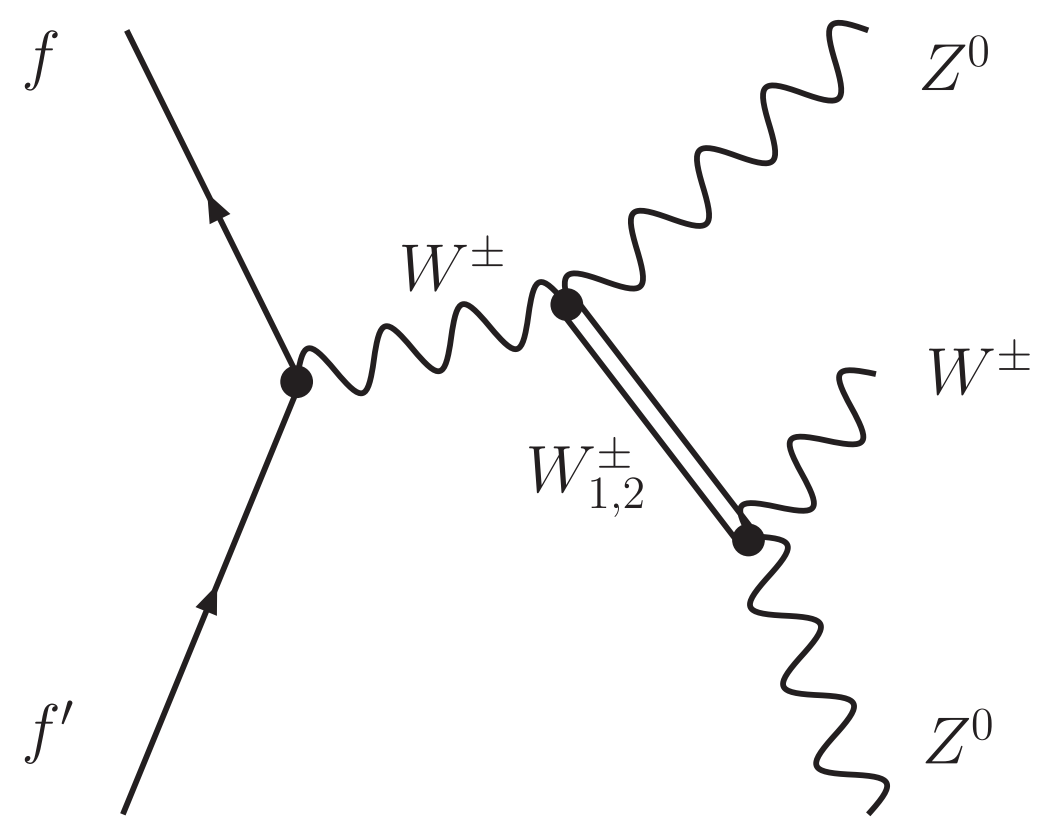
- These scenarios have largest couplings allowed by experimental constraints; many other scenarios can be studied

- We can also study properties of the resonances with more luminosity

  - Angular distributions
  - Couplings
  - $\dfrac{\Gamma(W_{1,2} \to WZ)}{\Gamma(W_{1,2} \to ff')}$

High Luminosity Signals: Fermiophobic

- 'Ideally delocalized' scenario: resonances decouple from SM fermions $g_{ffV} \cong 0$
- Fine tuned, but very few constraints
- Resonances produced via associated production



Higgsless:

(Matchev, Perelstein '05
He, et al '07)

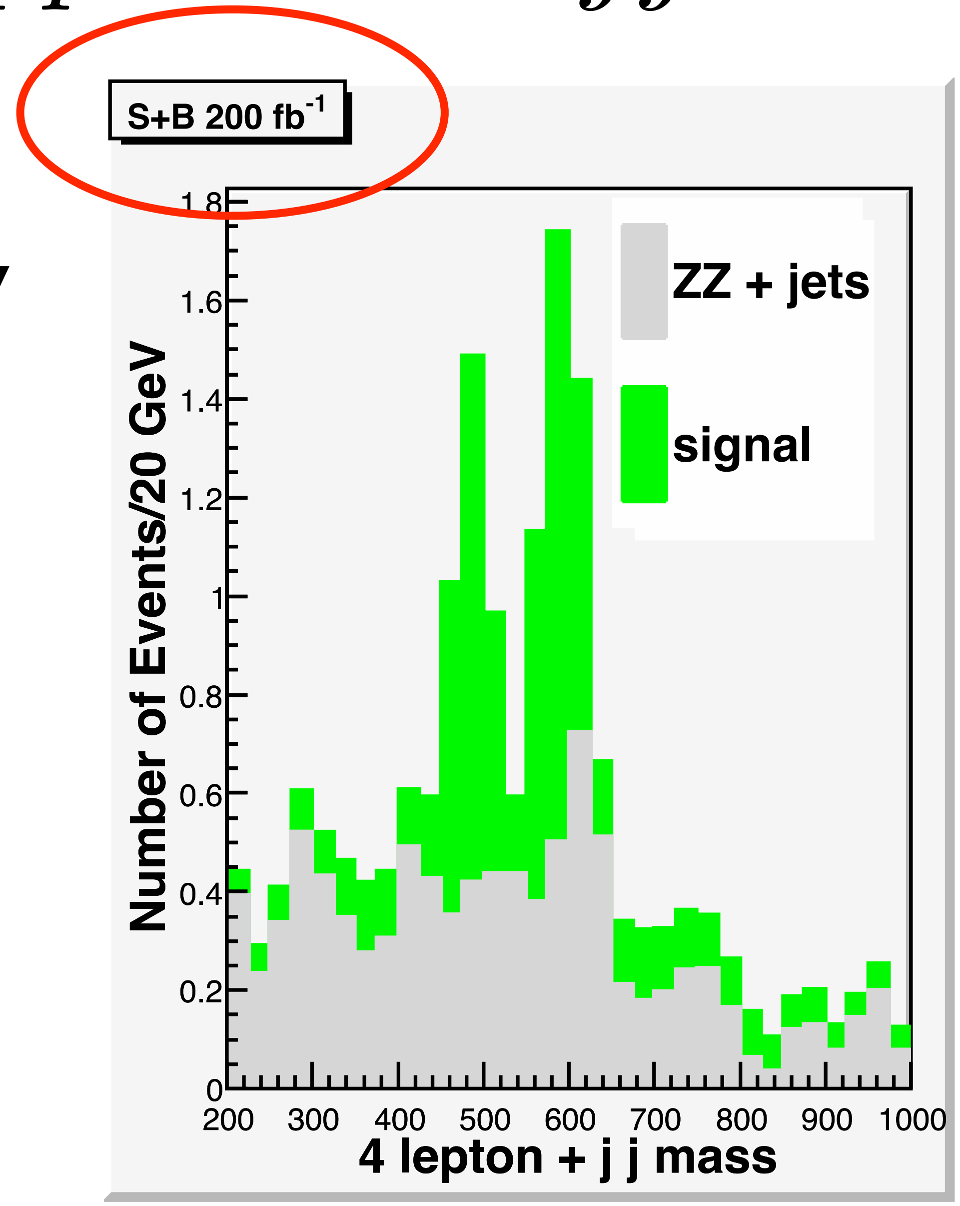
Fermiophobic Example: $pp \to 4\ell + jj$

- High luminosity necessary for discovery $\mathcal{L} \gtrsim 300\ \text{fb}^{-1}$
- Parton level estimates overly optimistic
- More clean signatures:

$$5\ell + \nu$$
$$3\ell + \nu + jj$$

- New signatures:

$$W + \gamma\gamma$$
$$W + \gamma + Z$$



1.) 2 jets, $p_T > 15$ GeV, $|\eta| < 4.5$
$|M_{jj} - M_W| < 20$ GeV

2.) $n_{lep} = 4, p_T > 10$ GeV, $|\eta| < 2.5$

3.) $p_{T,Z_{leading}} > 240$ GeV

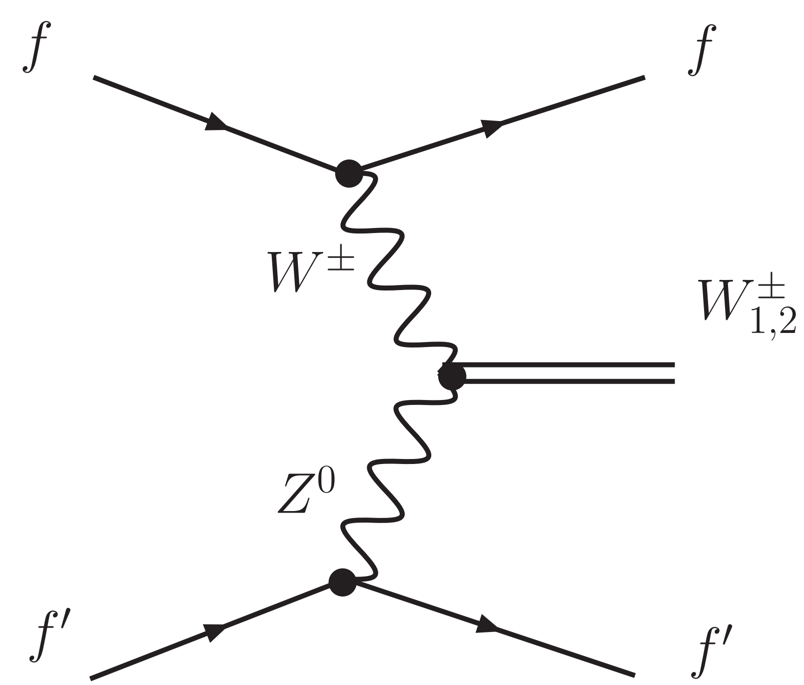
4.) $\sum_{ZZ+jj} p_T < 45$ GeV

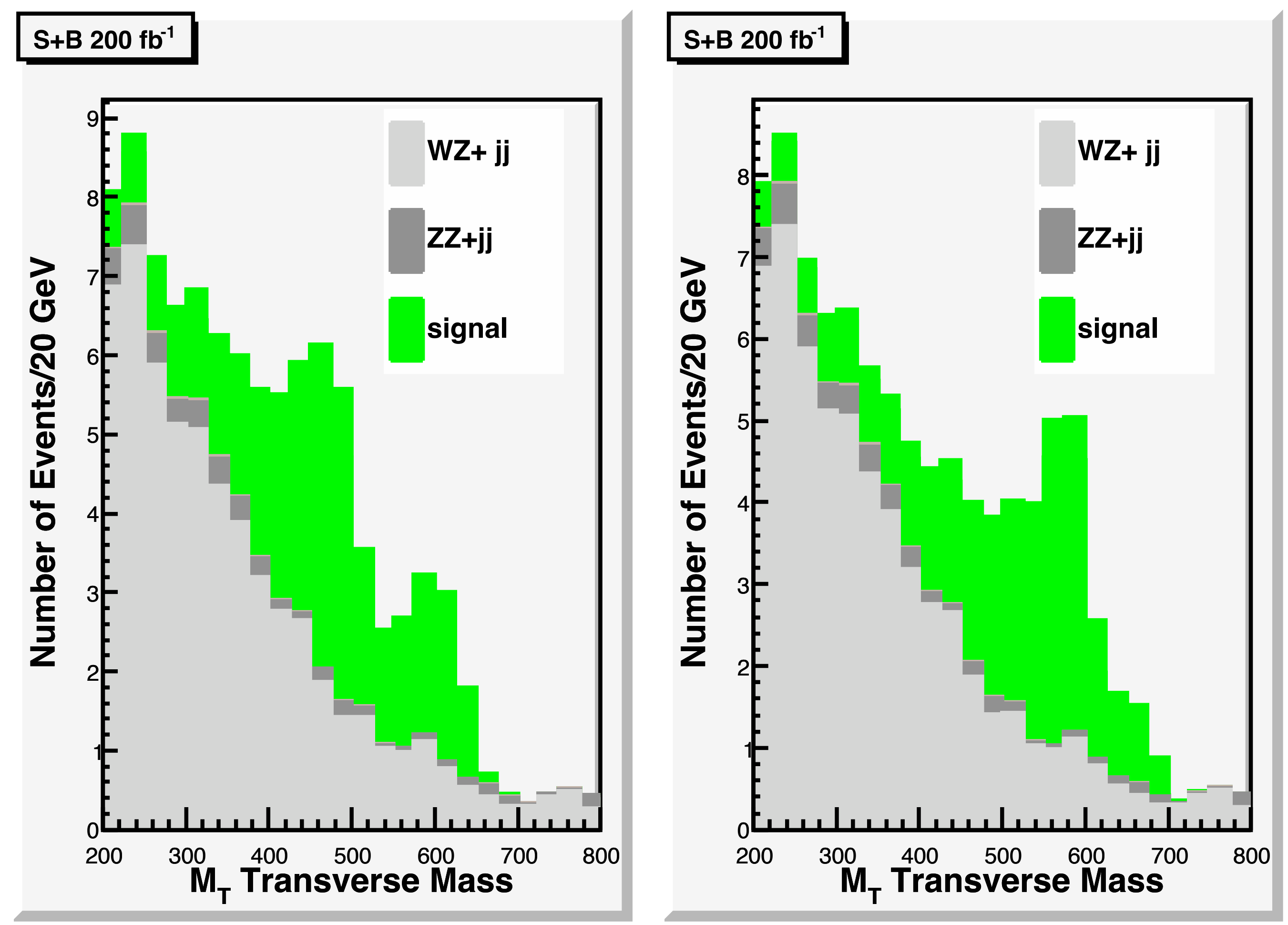
(cuts from He, et al)

Examples III: Vector Boson Fusion (VBF)

Regardless of g_{ffV}, VBF is important to observe at the LHC

Window into $W_L W_L \to W_L W_L$ scattering





- Two edges in M_T

Distinct features even if $g_{ffV} = 0$

1.) $n_{lep} = 3, p_T > 10$ GeV, $|\eta| < 2.5$

2.) $n_{jet} = 2, p_T > 30$ GeV, $2.0 < |\eta| < 4.5$

3.) $\Delta\eta_{jj} > 4.0$

4.) $|M_{\ell^+\ell^-} - M_Z| < 3\Gamma_Z$

5.) $p_{T,W},\ p_{T,Z} > 70$ GeV

(cuts from He, et al)

Conclusions:

- LHC is in the near future, yet detailed phenomenological studies of strong EW physics are lacking:

WHY?

  - simplest models ruled out
  - no models are implemented in parton level generators

- 5D Effective warp factor scheme: Generates $\mathcal{L}_{spin-1} + \mathcal{L}_{int}$ with only a few free parameters: $\ell_0, \ell_1, o_V, o_A, g_{ffV}$. We can use it to interpolate between many viable models

- New features in phenomenology:

  2 nearby peaks in Drell-Yan, VBF

  New phenomenology:

  Resonance $-\gamma - W$ couplings

in MadGraph!

- Many more scenarios to be studied!